Redefining the axion window

Based on arXiv:1610.07593 In collaboration with Luca Di Luzio (IPPP, Durham) and Federico Mescia (Barcelona U.)

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Outline

- The strong CP problem: a short review
- Types of axion models, and the QCD axion
- Dark Matter from axion misalignment
- The window for preferred hadronic axion models
- Experimental searches

The strong CP problem

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$$\mathcal{L}_{\rm QCD} = \sum_q \overline{q}\left(i\not{D} - m_q e^{i\theta_q}\right)q - \frac{1}{4}G_a^{\mu\nu}G_{\mu\nu}^a - \theta\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}_{\mu\nu}^a$$

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- Only the difference $\overline{\theta} = \theta - \theta_q$ has physical meaning

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- Change in θ is due to non invariance of path integral measure:

$$\mathcal{D}q\mathcal{D}\overline{q} \to \exp\left(-i\alpha \int d^4x\, \frac{\alpha_s}{4\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}\right) \mathcal{D}q\mathcal{D}\overline{q}$$

[Fujikawa (1979)]

A small value problem

- $\overline{\theta} \neq 0$ implies a non-zero neutron EDM [Baluni (1979), Crewther et al. (1979)]

$$d_n \approx \frac{e\,|\overline{\theta}|\,m_\pi^2}{m_n^3} \approx 10^{-16}\,|\overline{\theta}|\,e\,\mathrm{cm}$$

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Fig. 9. Generic topology of a class of divergent *CP* violating 14th-order diagrams in the Kobayashi-Maskawa model [21,22].

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  - Unlike $y_{e,u,d} \sim 10^{-6} \div 10^{-5}$ it evades explanations based on environmental selection [Ubaldi, 0811.1599]

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[Barr (1984), Nelson (1984)]

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  - Assume a global $U(1)_{PQ}$: (i) spontaneously broken; (ii) QCD anomalous
  - Implies a PGB of $U(1)_{PQ}$: the Axion. Shift symmetry: $a(x) \to a(x) + \delta\alpha\, f_a$

$$\mathcal{L}_{\rm eff} = \underbrace{\left(\overline{\theta} + \frac{a}{f_a}\right)}_{\theta_{\rm eff}(x)} \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu} - \frac{1}{2}\partial^\mu a \partial_\mu a + \mathcal{L}(\partial_\mu a, \psi)$$

Relaxation of $\Theta_{eff}(x) \longrightarrow 0$

- Minimum ground state energy in Euclidean V_4

$$e^{-V_4 E(\theta_{\rm eff})} = \int \mathcal{D}\varphi\, e^{-S_0 + i\theta_{\rm eff}\{G\tilde{G}\}} = \left| \int \mathcal{D}\varphi\, e^{-S_0 + i\theta_{\rm eff}\{G\tilde{G}\}} \right| \leq \int \mathcal{D}\varphi \left| e^{-S_0 + i\theta_{\rm eff}\{G\tilde{G}\}} \right| = e^{-V_4 E(0)}$$

[Vafa, Witten (1984)]

where $\{G\tilde{G}\} = \frac{\alpha_s}{8\pi} \int d^4x\, G^{\mu\nu} \tilde{G}_{\mu\nu}$, and using Schwartz inequality

- So $E(0) < E(\theta_{eff})$ and in the ground state the θ term is dynamically relaxed to 0.

Axion models

- **PQWW axion:**
  Axion identified with the phase of the Higgs in a 2HDM
  ($f_a \sim V_{EW}$ was quickly ruled out long ago) [Peccei, Quinn (1977), Weinberg (1978), Wilczek (1978)]

The need to require $f_a \gg V_{EW}$: "invisible axion"

- **DSFZ Axion:** SM quarks and Higgs charged under PQ.
  Requires 2HDM + 1 scalar singlet. SM leptons can also be charged.
  [Dine, Fischler, Srednicki (1981), Zhitnitsky (1980)]

- **KSVZ axion** (or QCD axion, or hadronic axion):
  All SM fields are neutral under PQ. QCD anomaly is induced by new quarks, vectorlike under the SM, chiral under PQ.
  [Kim (1979), Shifman, Vainshtein, Sakharov (1980)]

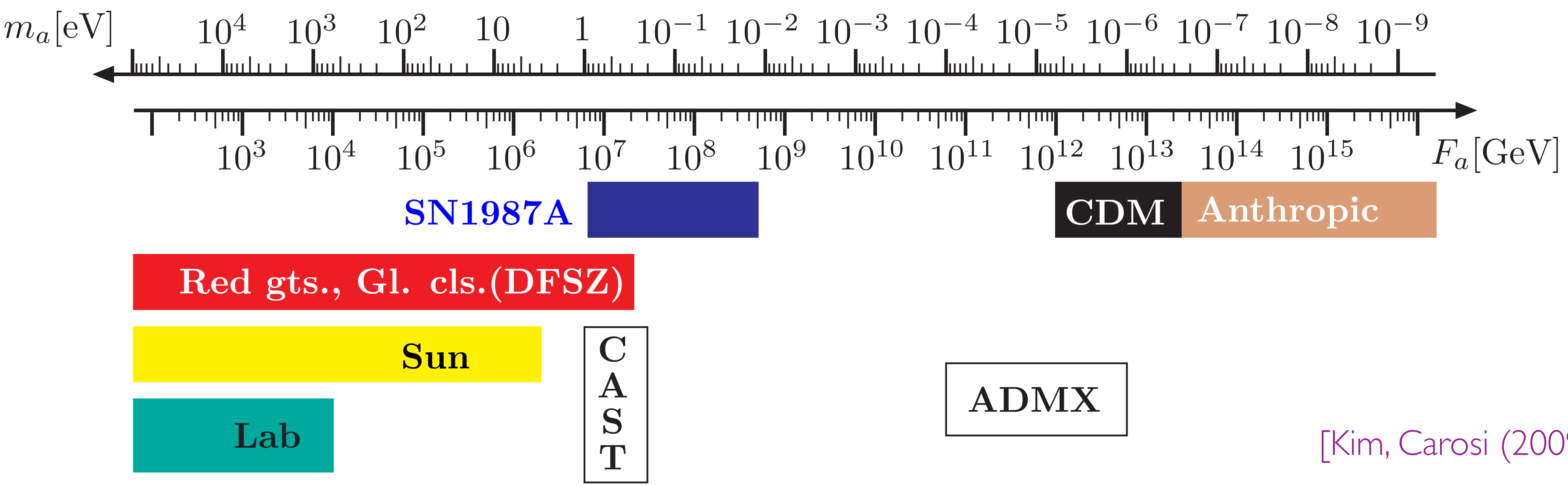
Model independent features

- Axion mass: $\sim 1/f_a$ $\quad m_a \simeq m_\pi \frac{f_\pi}{f_a} \simeq 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a}$

- All axion couplings: $\sim 1/f_a$

The lighter is the axion, the weaker are its interactions

Axion Landscape:



[Kim, Carosi (2009)]

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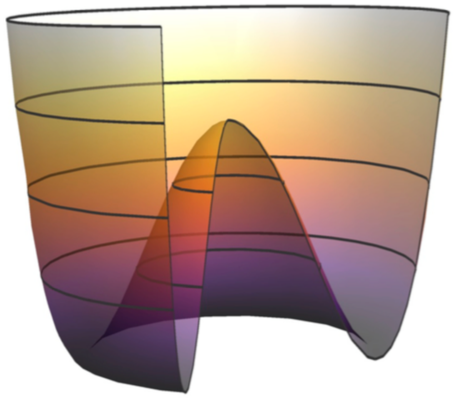
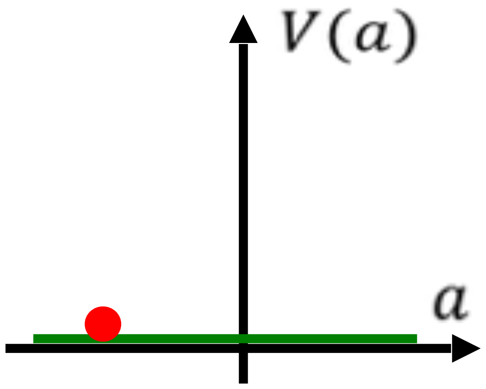
  $U(1)_{PQ}$ broken only spontaneously,

  $m_a = 0$, $\langle a_0 \rangle = \theta_0 f_a \sim f_a$





$$\ddot{a} + 3H\dot{a} + m_a^2(T) f_a \sin\left(\frac{a}{f_a}\right) = 0$$

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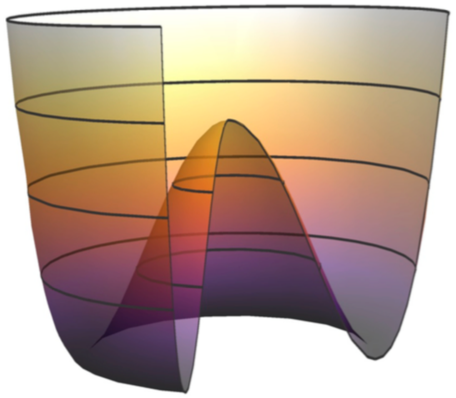

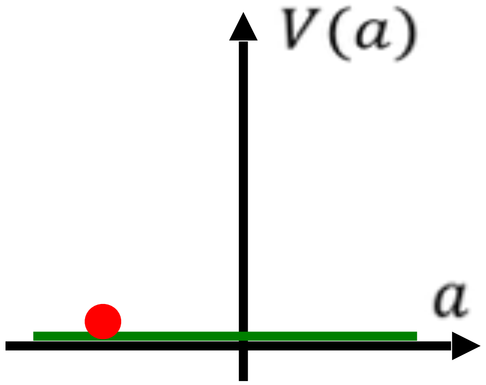

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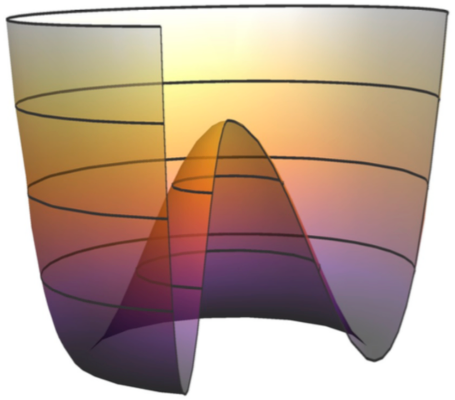

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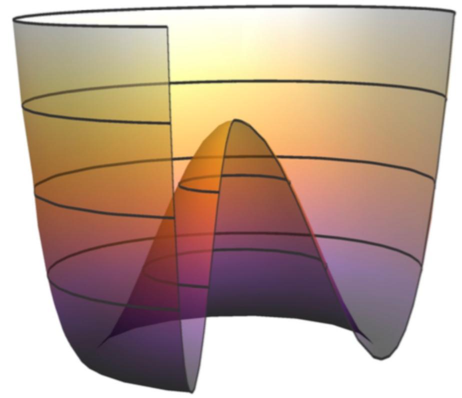
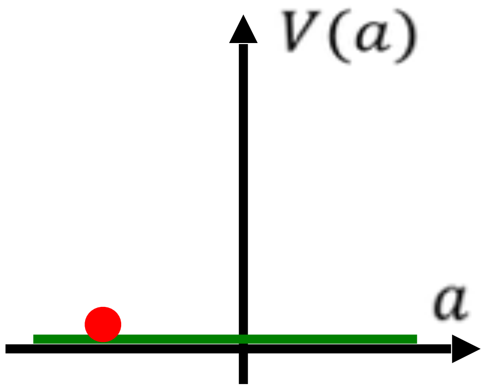


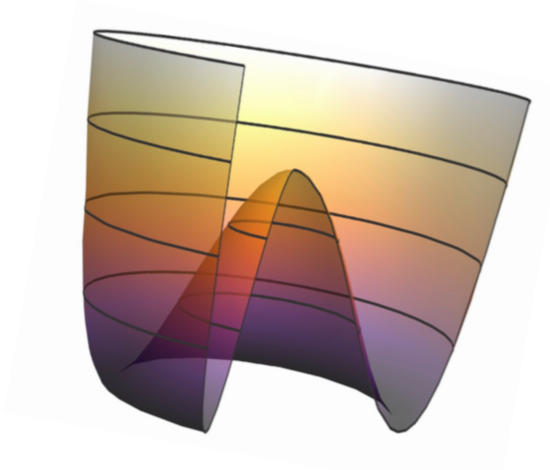


- **As soon as $T \sim \Lambda_{QCD}$:**

  $U(1)_{PQ}$ explicit breaking (instanton effects)

  $m_a(T)$ turns on. When $m_a(T) > H \sim 10^{-9}$ eV,

  $\langle a_0 \rangle \longrightarrow 0$ and starts oscillating undamped



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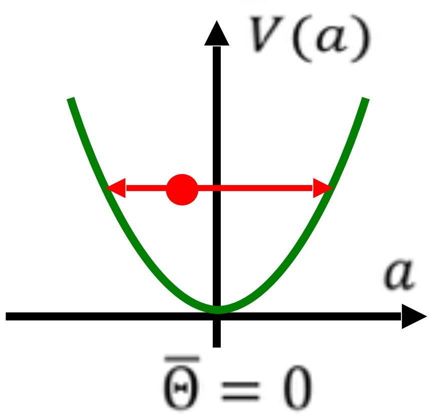

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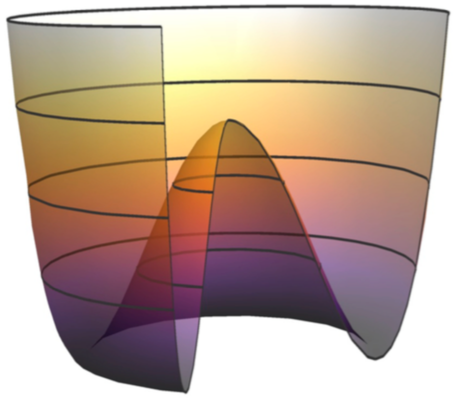

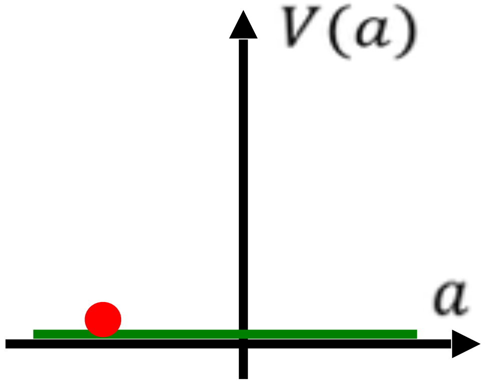

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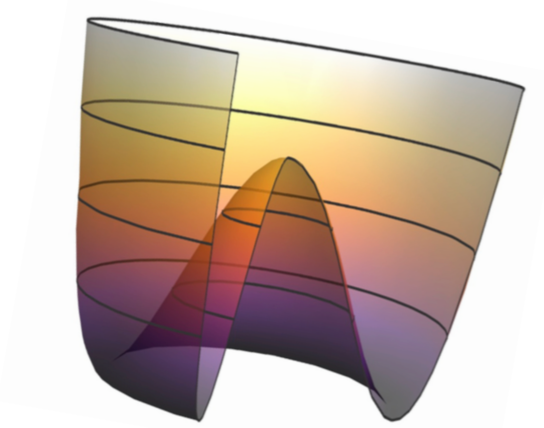

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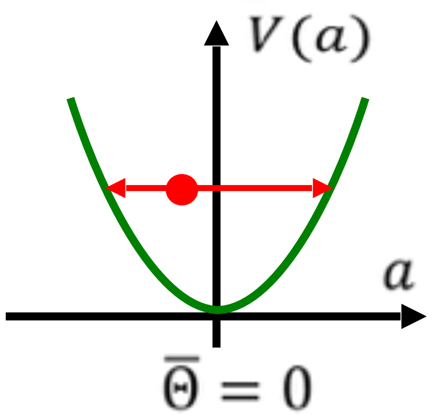

- **Energy stored in oscillations behaves as CDM**

[Preskill, Wise, Wilczek (1983), Abott, Sikivie (1983), Dine, Fischler (1983)]

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- From recent lattice QCD calculations, [Bonati et al. 1512.06746, Petreczky et al. 1606.03145, Borsanyi et al. 1606.07494]

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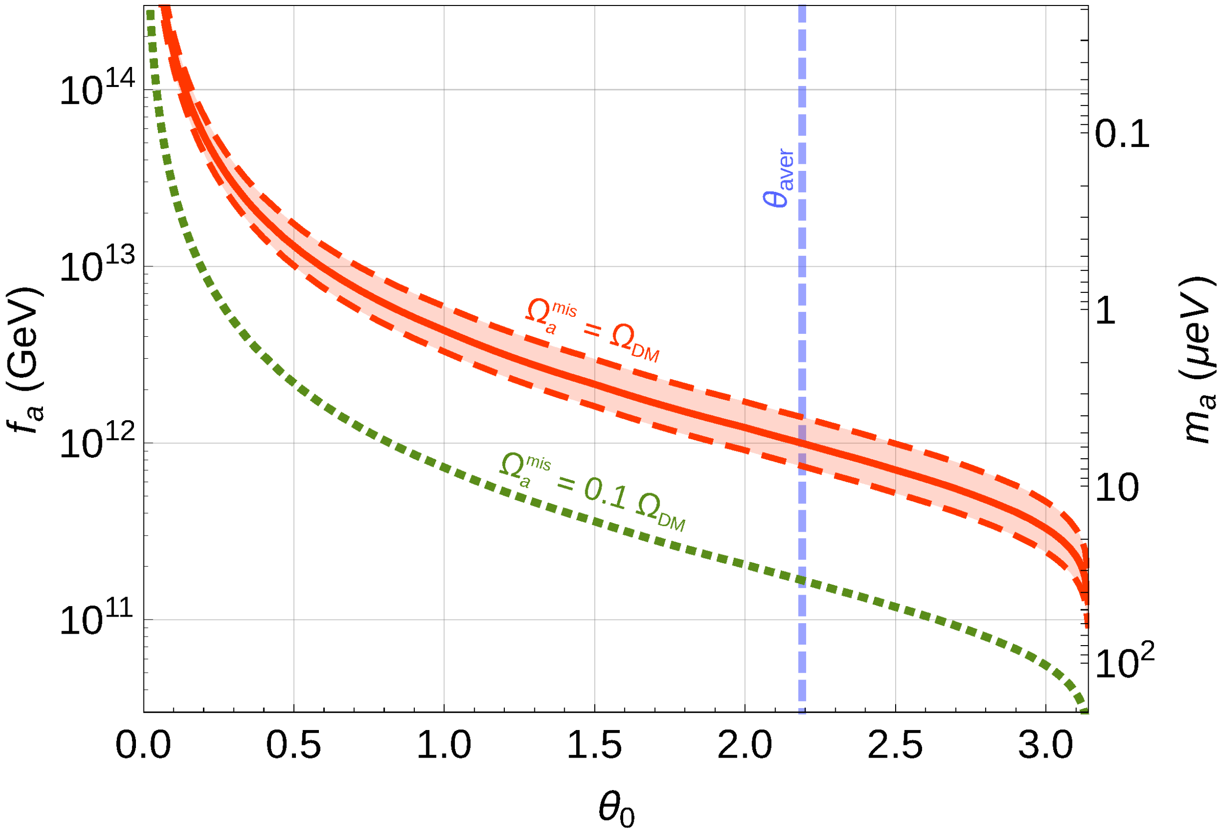

- Value of θ_0 depends on the scale of inflation versus the PQ breaking scale f_a

  — $U(1)_{PQ}$ broken after inflation: average over several Universe patches : $\langle\theta_0\rangle = \pi/\sqrt{3}$

  — $U(1)_{PQ}$ broken before inflation: in the whole observable Universe the same random value of θ_0

  — "Antropic Axion": $f_a \gg 10^{12}$ GeV is allowed only if $\theta_0 \ll 1$

Astrophysical lower limit on f_a

- Astrophysical bounds

[For a collection see e.g. Raffelt, hep-ph/0611350]

- Star evolution, RG lifetime $g_{a\gamma\gamma} \lesssim 6.6 \times 10^{-11}\ \mathrm{GeV}^{-1}$
- White dwarf cooling $g_{aee} \lesssim 1.3 \times 10^{-13}\,\mathrm{GeV}^{-1}$
- Supernova SN1987A $g_{aNN} \lesssim 3 \times 10^{-7}\ \mathrm{GeV}^{-1}$ $\longrightarrow$ $f_a \gtrsim 2 \times 10^{8}\ \mathrm{GeV}$

New search strategies

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- **Some new search possibilities which do not depend on $g_{a\gamma\gamma}$**

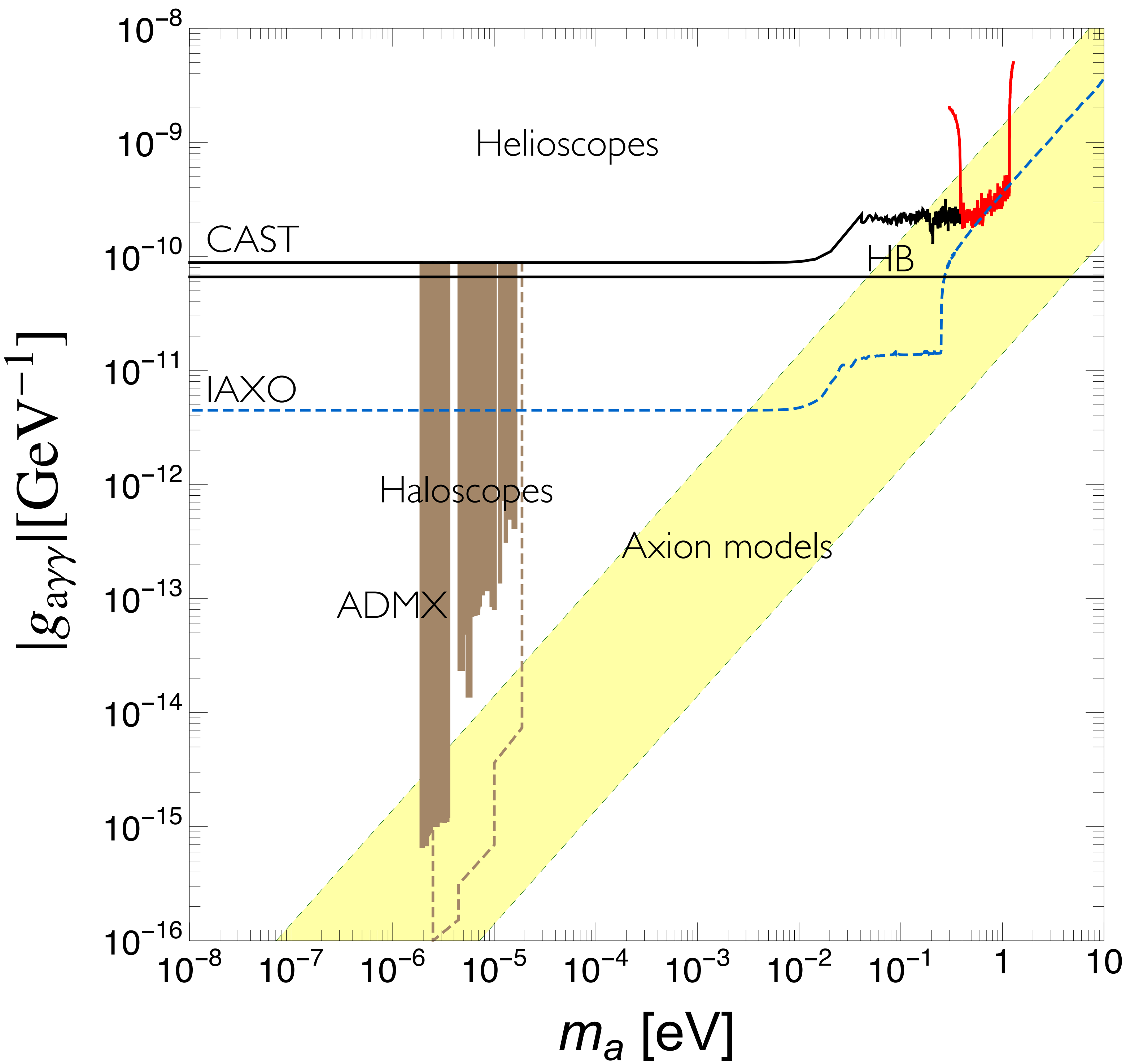
  - **Cosmic Axion Spin Precession Experiment (CASPEr).** [Budker et al., 1306.6089]

    Background axion field might induce an oscillating neutron EDM, which can be detected via NMR techniques.

  - **Black hole super-radiance (mainly bounds for ALPs)** [Arvanitaki, Dubovsky 1004.3558]

    very light axions with a Compton wavelength comparable with that of a black hole can form a gravitational bound state and irradiate energy via gravitational waves

The "usual" axion window



$$g_{a\gamma\gamma} = \frac{m_a}{\mathrm{eV}} \frac{2.0}{10^{10}\ \mathrm{GeV}} \left(\frac{E}{N} - 1.92\right)$$

$$|E/N - 1.92| \in [0.07, 7]$$

[Particle Data Group (since end of 90's). Chosen to include some representative models from: Kaplan, NPB 260 (1985), Cheng, Geng, Ni, PRD 52 (1995), Kim, PRD 58 (1998)]

Hadronic axions (KSVZ)

- Field content KSVZ

Field	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{PQ}$
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Φ	0	1	1	0	1

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- PQ charges carried by SM-vectorlike quarks $Q = Q_L + Q_R$

- Original model assumes Q ~ (3,1,0) [only $\mathcal{C}_Q \neq I$ is in fact required].

  However in general:

$$\partial^\mu J_\mu^{PQ} = \frac{N\alpha_s}{4\pi} G\cdot\tilde{G} + \frac{E\alpha}{4\pi} F\cdot\tilde{F}$$

$$N = \sum_Q (\mathcal{X}_L - \mathcal{X}_R)\; T(\mathcal{C}_Q)$$

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} anomaly coeff.

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- and by SM singlet Φ containing the "invisible" axion ($V_a \gg v_{\rm EW}$)

$$\Phi(x) = \frac{1}{\sqrt{2}}\left[\rho(x) + V_a\right] e^{ia(x)/V_a}$$

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- Generic QCD axion Lagrangian: $\mathcal{L}_a = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm PQ} - V_{H\Phi} + \mathcal{L}_{Qq}$ $\qquad |\mathcal{X}_L - \mathcal{X}_R| = 1$

- $\mathcal{L}_{\rm PQ} = |\partial_\mu \Phi|^2 + \overline{Q} i \not{D} Q - (y_Q \overline{Q}_L Q_R \Phi + \text{H.c.})$ → $m_Q = y_Q V_a/\sqrt{2}$

- $V_{H\Phi} = -\mu_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4 + \lambda_{H\Phi} |H|^2 |\Phi|^2$ → $m_\rho \sim V_a$

- $\mathcal{L}_{Qq}$: d ≤ 4 couplings to SM quarks, depend on Q-gauge quantum numbers, but apparently also on their PQ charges

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- if $\mathcal{L}_{Qq} \neq 0$ $U(1)_Q$ x $U(1)_B$ is broken to `extended' $U(1)_{B'}$. Q's can decay

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$$U(1)_{Q_L} \times U(1)_{Q_R} \times U(1)_{\Phi} \xrightarrow{y_Q \neq 0} U(1)_{\rm PQ} \times U(1)_{\rm Q}$$

$$\mathcal{L}_{\rm PQ} = |\partial_\mu \Phi|^2 + \overline{Q} i \not{D} Q - (y_Q \overline{Q}_L Q_R \Phi + {\rm H.c.})$$

- $U(1)_Q$ is Q-baryon number. Exact $U(1)_Q \Rightarrow$ Q stability. [E.g. Q ~ (3,1,0)]

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$V_\Phi^{d>4} \ni \frac{\Phi^N}{M_{\rm Planck}^{N-4}}$ → If N < 10 would spoil the PQ solution

[Kamionkowski, March-Russell (1992), Holman et al. (1992), Barr, Seckel (1992)]

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$$Q_L \to Q_L\,, \quad Q_R \to \omega^{\mathbb{N}-1} Q_R\,, \quad \Phi \to \omega\,\Phi\,,$$ where $$\omega \equiv e^{i2\pi/\mathbb{N}}$$

$\mathbb{Z}_\mathbb{N}(q)$	$d \leq 4$	$d = 5$	$(\mathcal{X}_L, \mathcal{X}_R)$
1	$\overline{Q}_L d_R$	$\overline{Q}_L \gamma_\mu q_L\,(D^\mu H)^\dagger$	$(0,-1)$
ω	$\overline{Q}_L d_R \Phi^\dagger$		$(-1,-2)$
$\omega^{\mathbb{N}-2}$	–	$\overline{Q}_L d_R \Phi^2,\ \overline{Q}_R q_L H^\dagger \Phi$	$(2,1)$
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Ensures that the min. dimension of the $U(1)_{PQ}$ breaking operators in $V_\Phi^{d>4}$ is $\mathbb{N}$. The dim of the $U(1)_Q$ breaking opts. depends on $\mathbb{Z}_\mathbb{N}(q)$

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Cosmological constraints on τ_Q

- Strongly interacting long-lived particles are an issue in cosmology

EW interactions out of equilibrium

Big Bang Nucleosynthesis (BBN)

Recombination

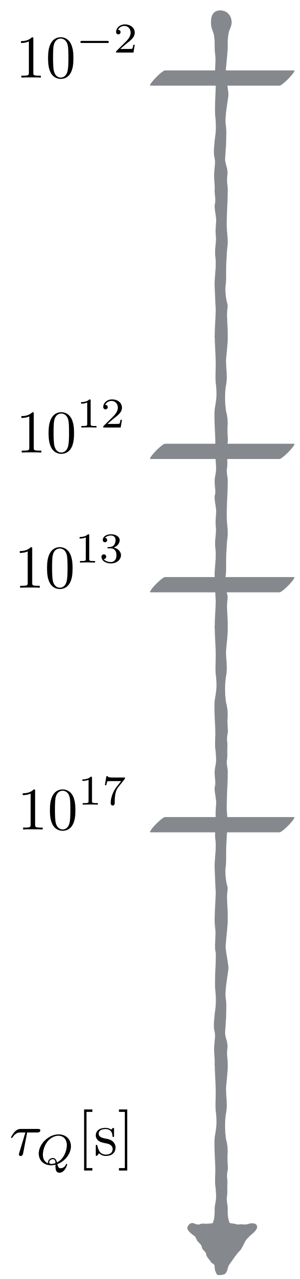
CMB radiation

Diffuse γ-rays

Age of the Universe

Excess Universe energy density

Anomalously heavy isotopes



[See e.g. "Non-collider searches for stable massive particles", Burdin et al. Physics Reports 582 (2015) 1–52]

Cosmological constraints on τ_Q

- Assume $m_Q \ll T_{reheating}$ (thermal distribution of Q's as initial condition)

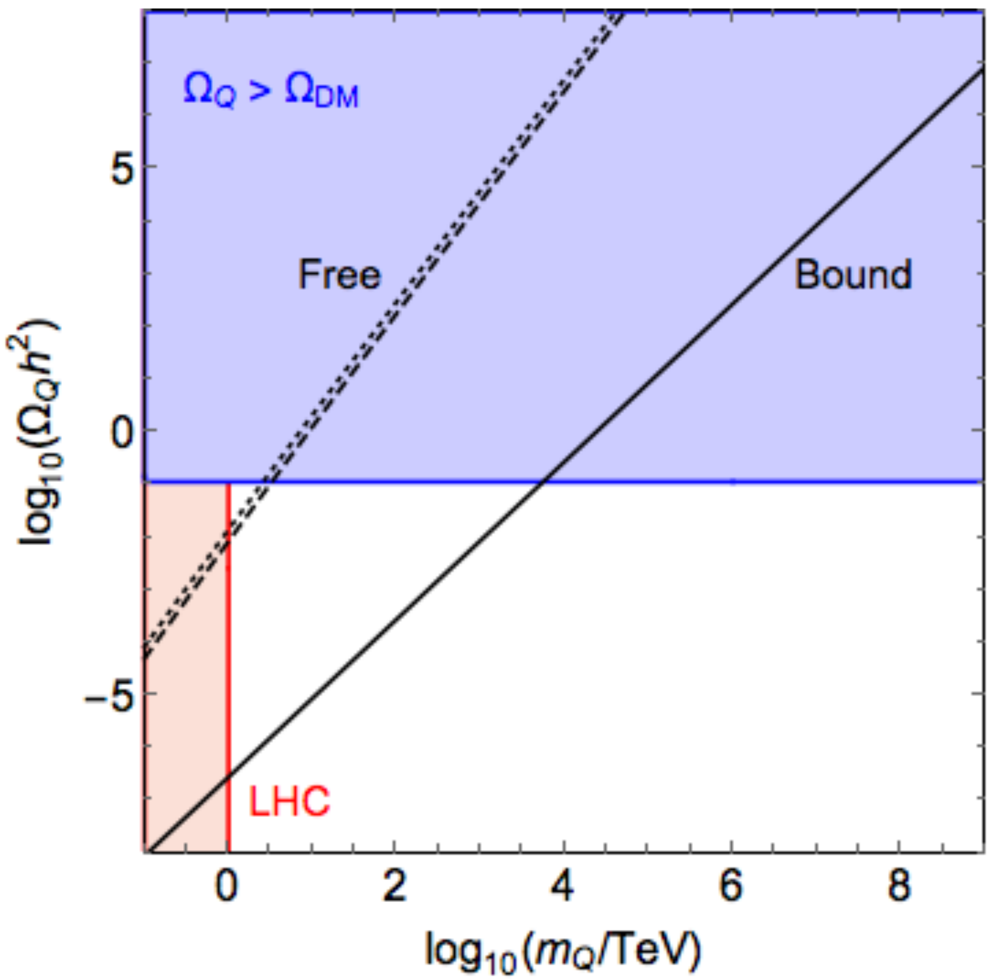
  Free quark annihilation: excess $\Omega_Q > \Omega_{DM}$ would allow to exclude $\tau_Q \gtrsim \tau_{Univ}$

- At $T < \Lambda_{QCD}$ bound state formation can catalyse annihilations.

  E.g. for color triplets: $Q^*q + Qqq \rightarrow [Q^*Q] + qqq$

- However QQ…, QQQ bound bound states would hinder it.

- A reliable estimate of Ω_Q remains an open issue !



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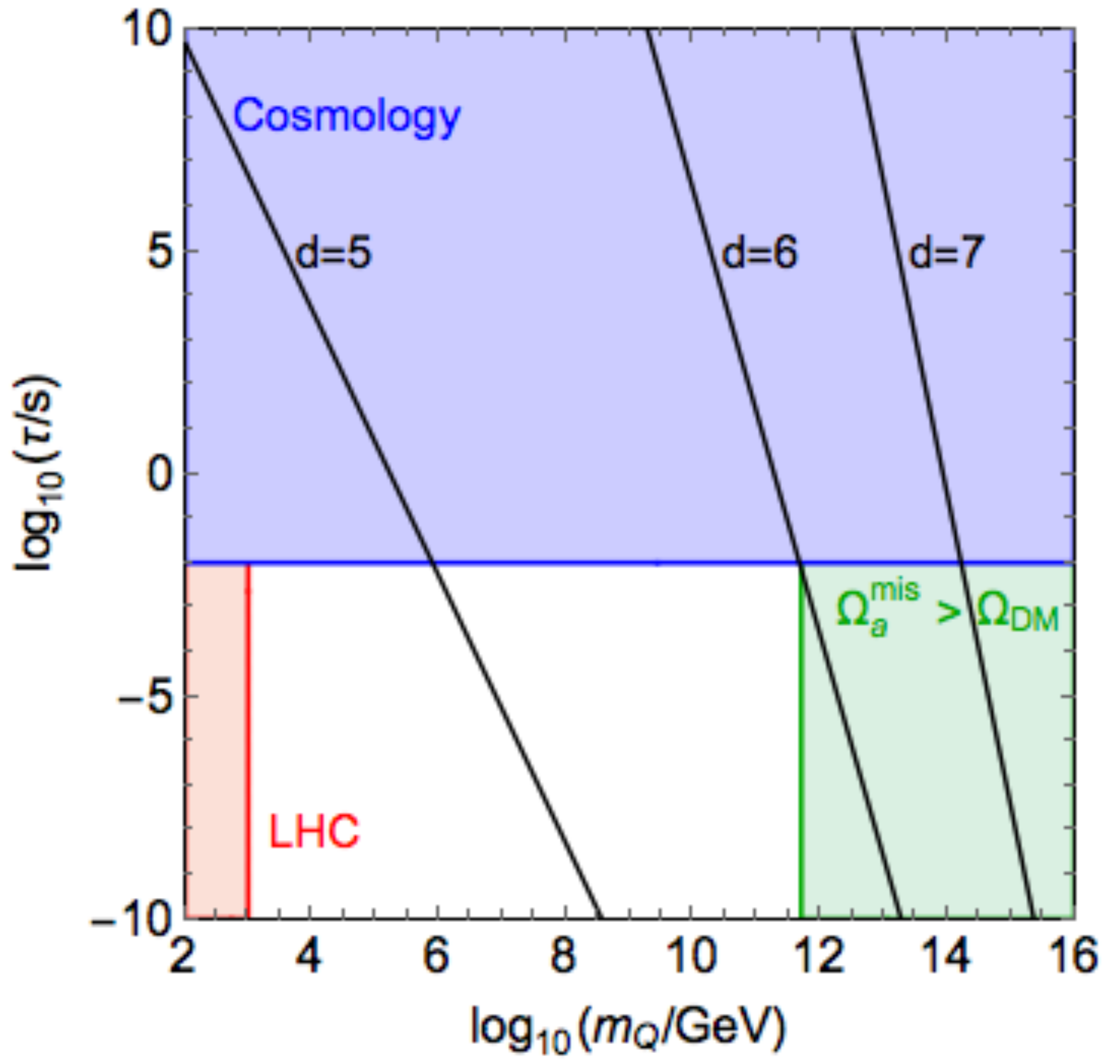
  - Decays via higher order operators are fast enough only for d=5 and $m_Q \gtrsim 800$ TeV.

$$\mathcal{L}_{Qq}^{d>4} = \frac{1}{M_{\rm Planck}^{(d-4)}} \mathcal{O}_{Qq}^{d>4} + \text{h.c.}$$



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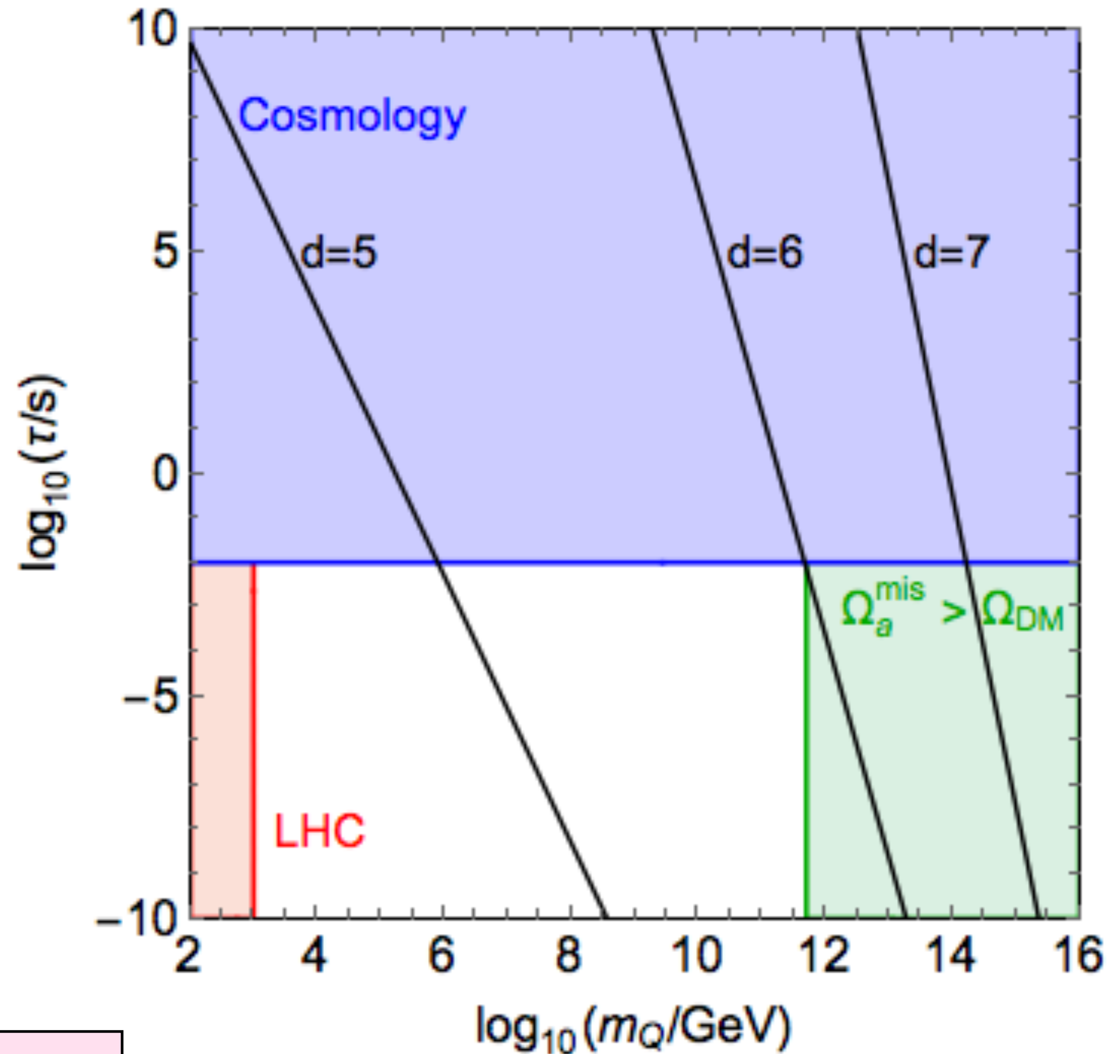

Therefore, "safe" R(Q) must allow for gauge invariant d=4 or d=5 operators

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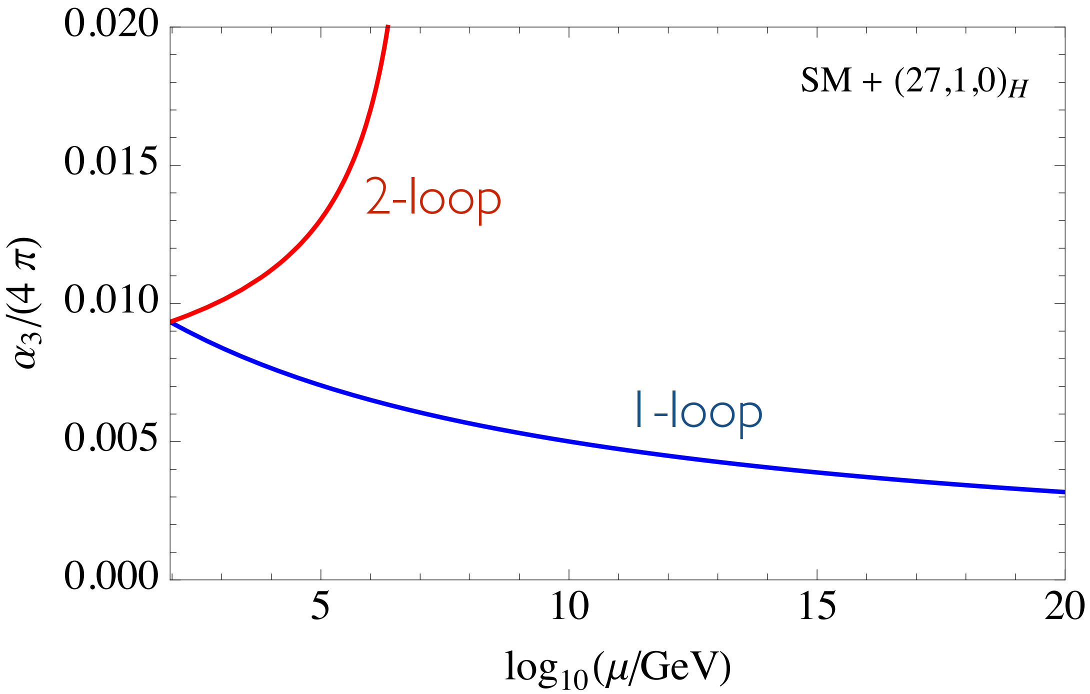
Two-loop β functions help to avoid spurious results from accidental cancellations in 1-loop β functions...

[Di Luzio, Gröber, Kamenik, Nardecchia, 1504.00359]



Phenomenologically preferred Q's

R_Q	$\mathcal{O}_{Qq}$	$\Lambda^{2-\text{loop}}_{\text{Landau}}[\text{GeV}]$	E/N
$(3,1,-1/3)$	$\overline{Q}_L d_R$	$9.3\cdot 10^{38}(g_1)$	$2/3$
$(3,1,2/3)$	$\overline{Q}_L u_R$	$5.4\cdot 10^{34}(g_1)$	$8/3$
$(3,2,1/6)$	$\overline{Q}_R q_L$	$6.5\cdot 10^{39}(g_1)$	$5/3$
$(3,2,-5/6)$	$\overline{Q}_L d_R H^\dagger$	$4.3\cdot 10^{27}(g_1)$	$17/3$
$(3,2,7/6)$	$\overline{Q}_L u_R H$	$5.6\cdot 10^{22}(g_1)$	$29/3$
$(3,3,-1/3)$	$\overline{Q}_R q_L H^\dagger$	$5.1\cdot 10^{30}(g_2)$	$14/3$
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$(3,3,-4/3)$	$\overline{Q}_L d_R H^{\dagger 2}$	$3.5\cdot 10^{18}(g_1)$	$44/3$
$(\overline{6},1,-1/3)$	$\overline{Q}_L \sigma_{\mu\nu} d_R G^{\mu\nu}$	$2.3\cdot 10^{37}(g_1)$	$4/15$
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$(8,1,-1)$	$\overline{Q}_L \sigma_{\mu\nu} e_R G^{\mu\nu}$	$7.6\cdot 10^{22}(g_1)$	$8/3$
$(8,2,-1/2)$	$\overline{Q}_R \sigma_{\mu\nu} \ell_L G^{\mu\nu}$	$6.7\cdot 10^{27}(g_1)$	$4/3$
$(15,1,-1/3)$	$\overline{Q}_L \sigma_{\mu\nu} d_R G^{\mu\nu}$	$8.3\cdot 10^{21}(g_3)$	$1/6$
$(15,1,2/3)$	$\overline{Q}_L \sigma_{\mu\nu} u_R G^{\mu\nu}$	$7.6\cdot 10^{21}(g_3)$	$2/3$

$$g_{a\gamma\gamma} = \frac{m_a}{\text{eV}}\,\frac{2.0}{10^{10}\ \text{GeV}}\left(\frac{E}{N} - 1.92(4)\right)$$

$$\frac{E}{N} = \frac{\sum_Q \mathcal{Q}_Q^2}{\sum_Q T(\mathcal{C}_Q)}$$

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- Only 15 Q's survive:

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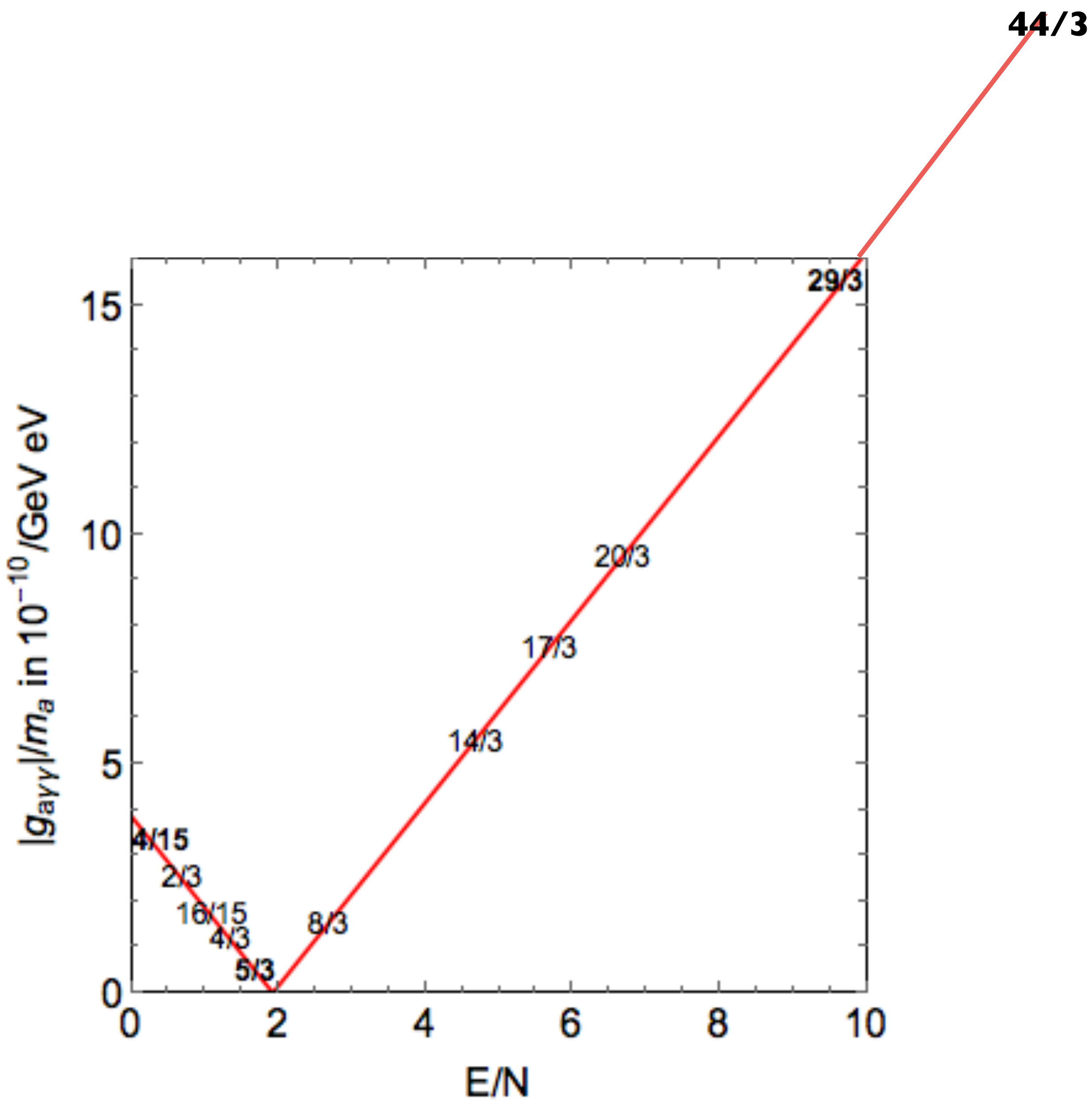
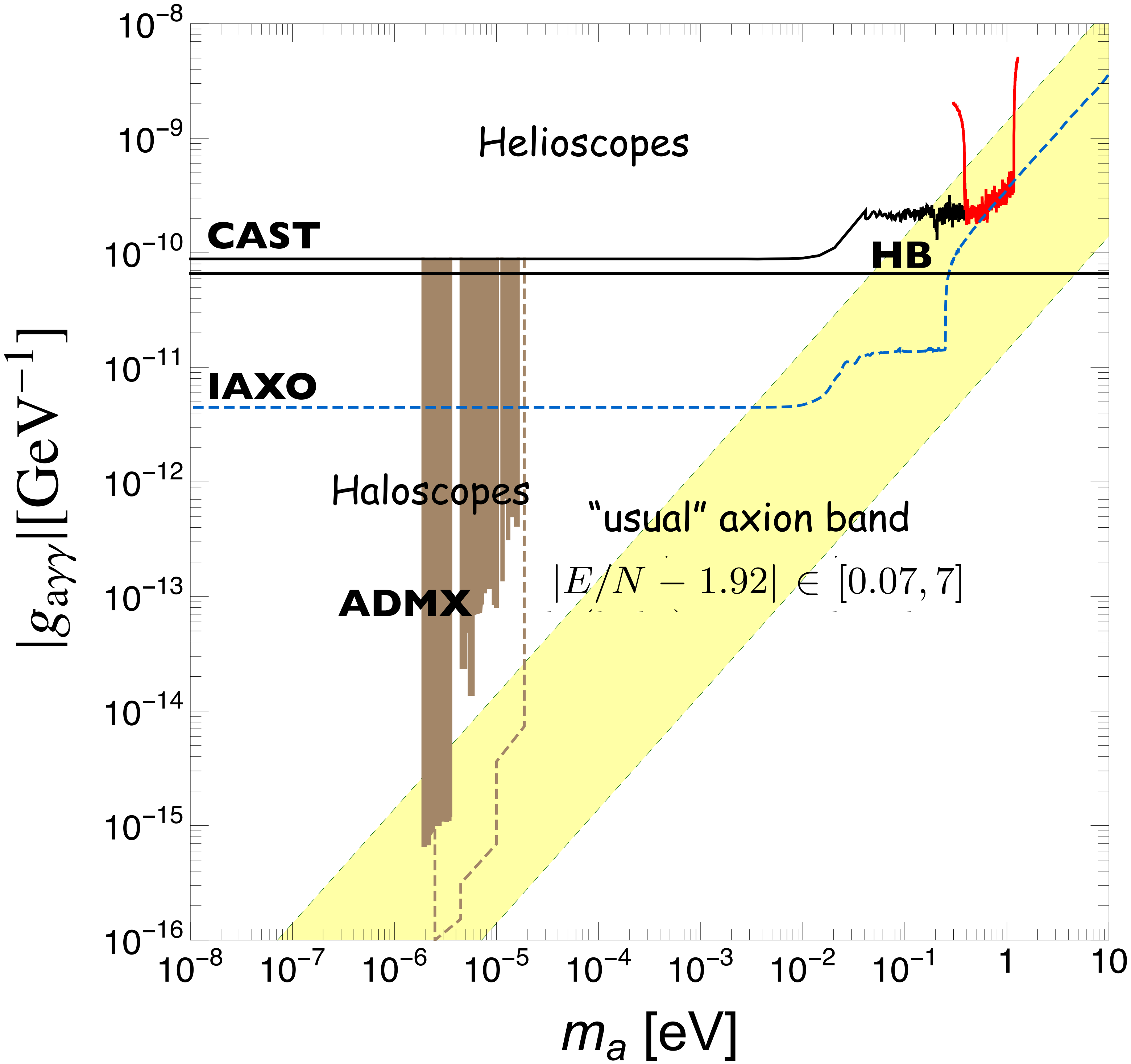


Redefining the axion window



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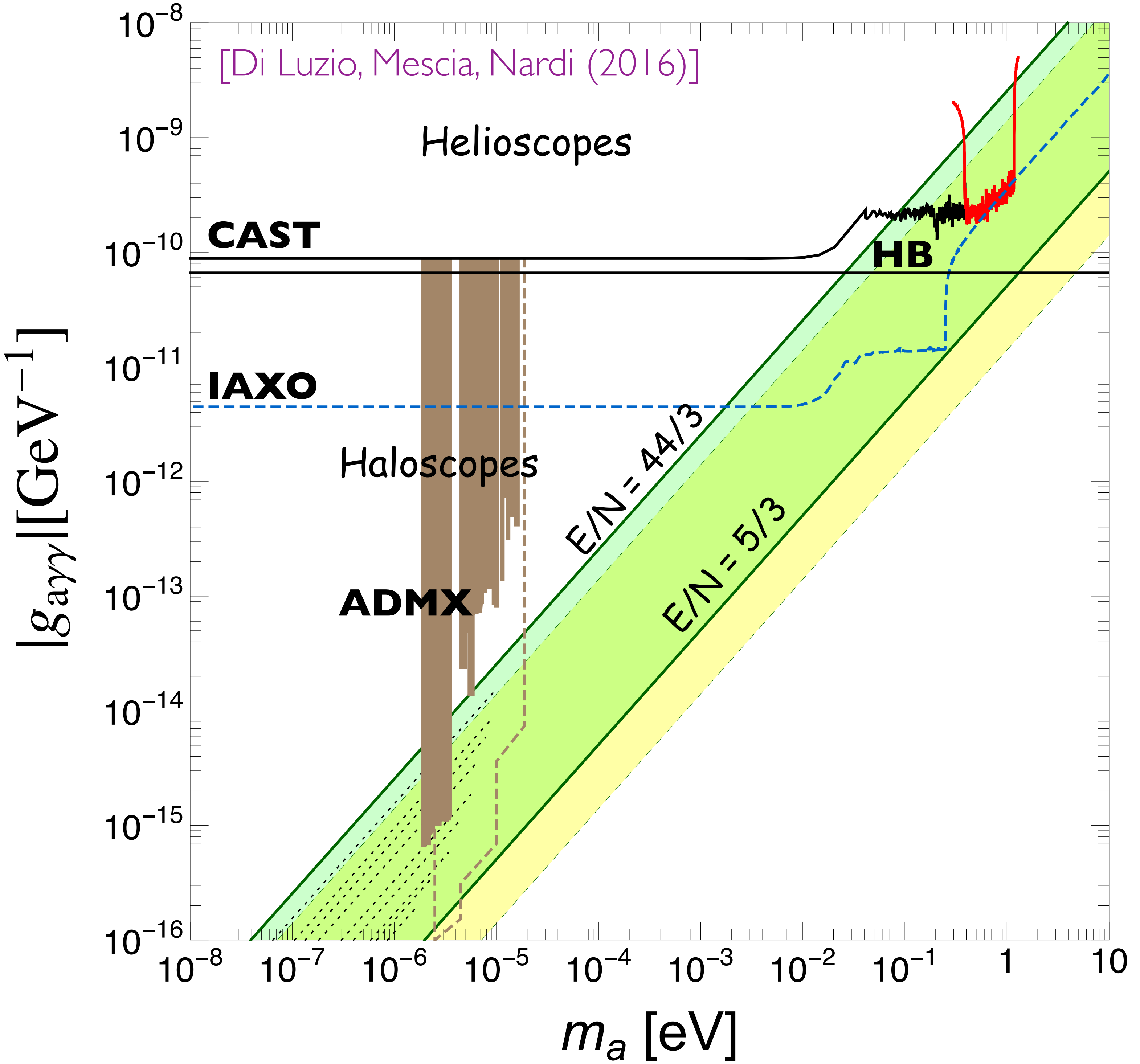

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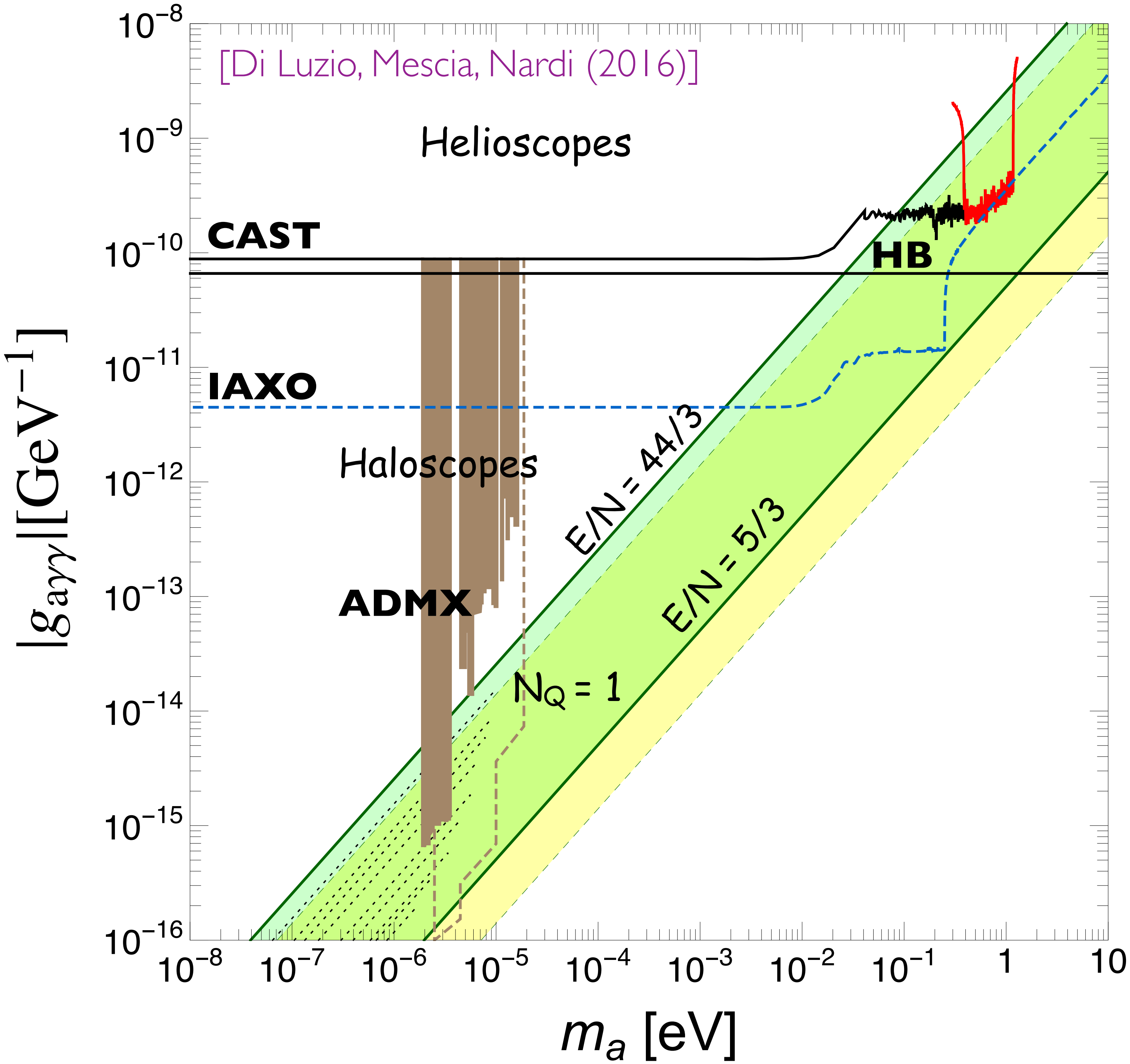

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[Theoretical error from NLO χPT
Grilli di Cortona et al., 1511.02867]

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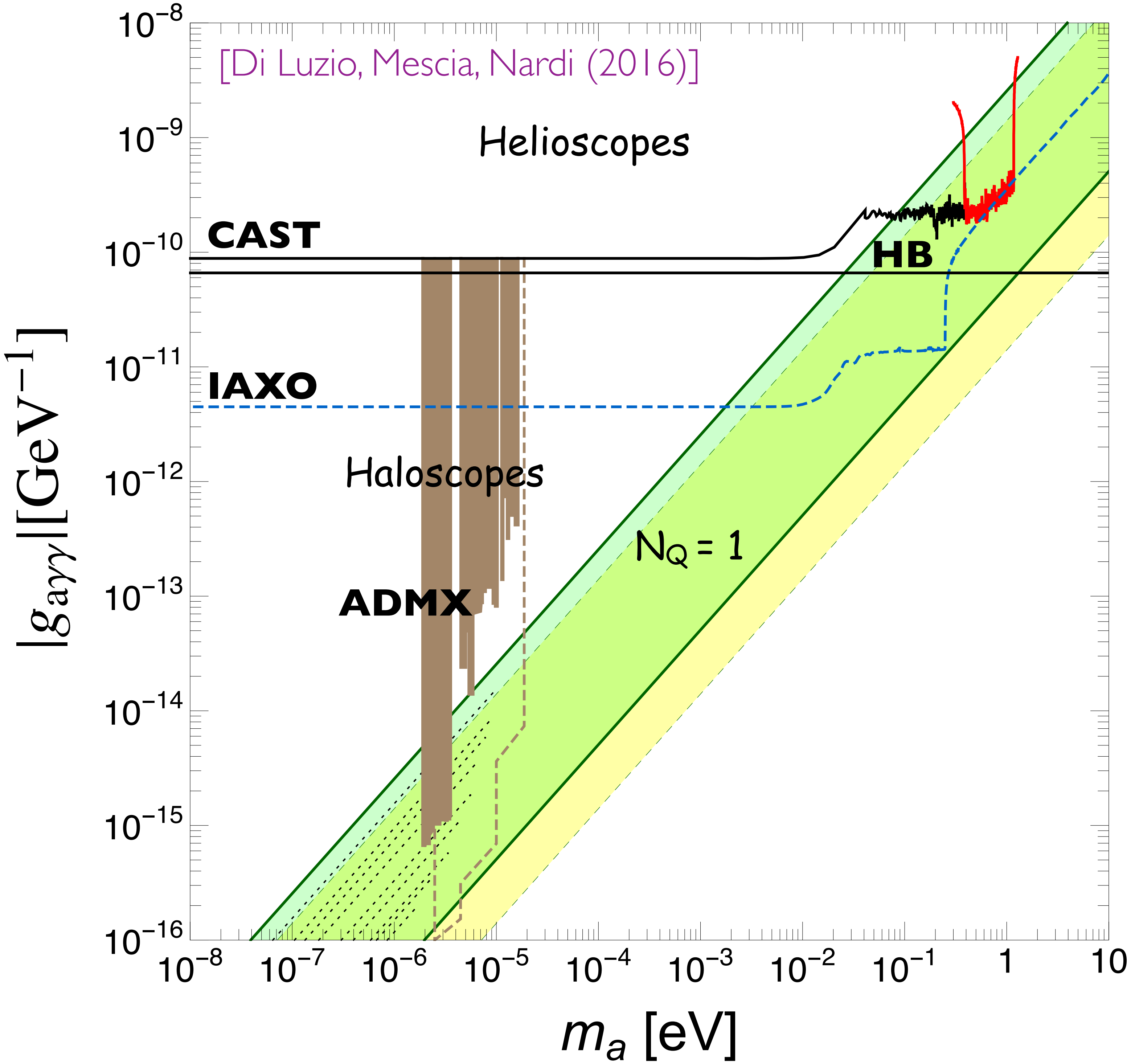
[Di Luzio, Mescia, Nardi (2016)]
Helioscopes
CAST
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$N_Q = 1$
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m_a [eV]
10^{-8}
10^{-9}
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1
10

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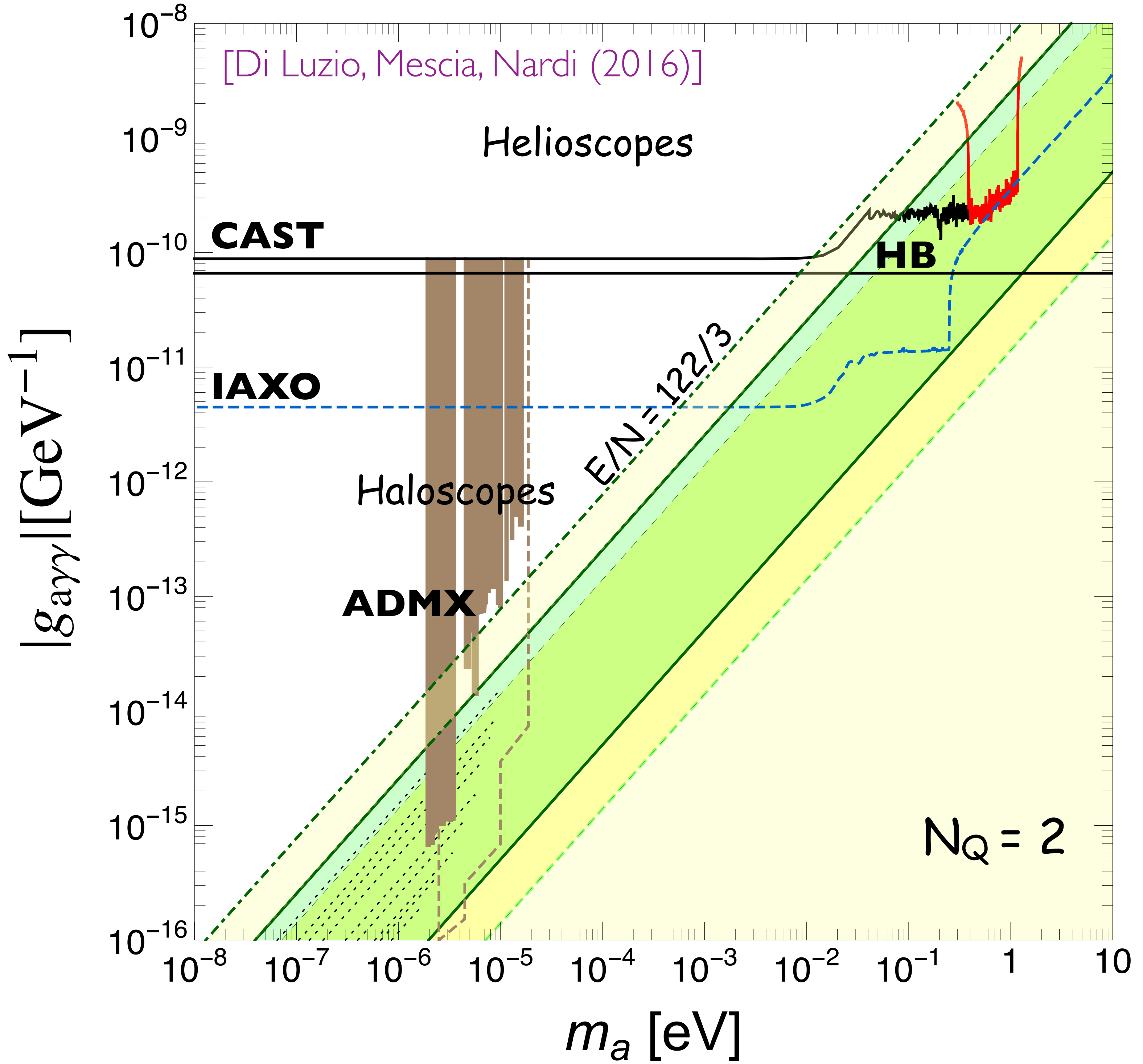

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- Here: axion window defined through precise pheno requirements.

Backup slides

Unificaxion ?

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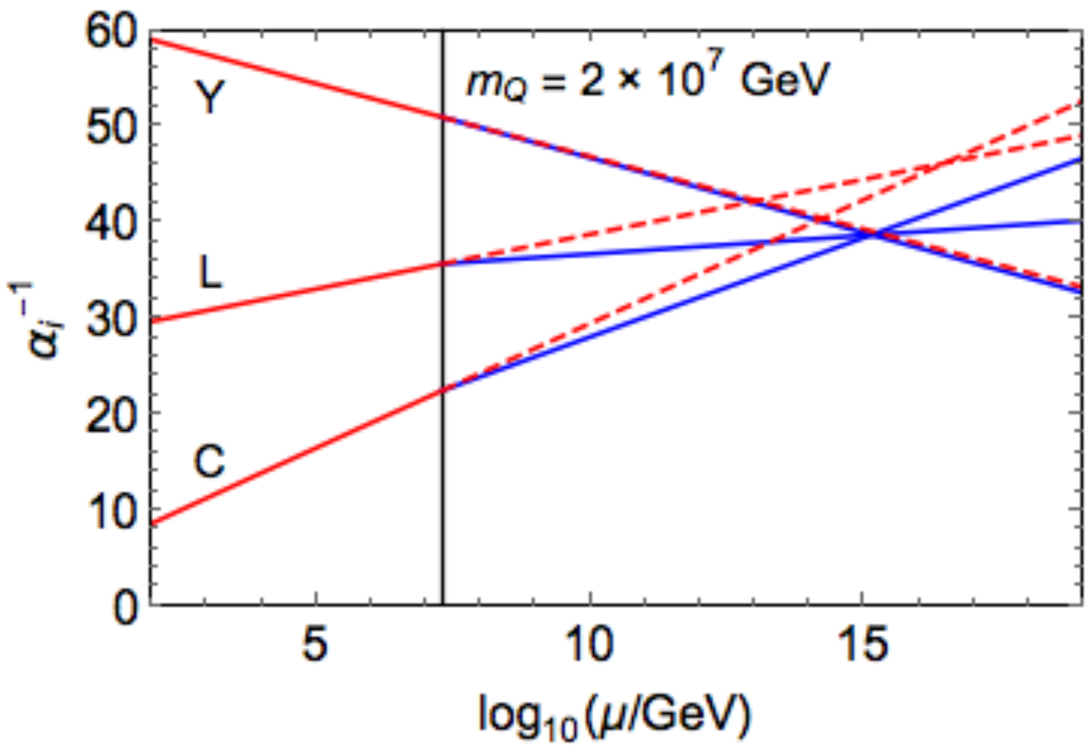
  - out of all our 15 cases, just one works fine: Q ~ (3, 2, 1/6)



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  - out of all our 15 cases, just one works fine: Q ~ (3, 2, 1/6)
- Conceiving a UV model remains, however, a challenge
  - $Q \in \psi_{\rm GUT}$
  - $m_Q \lesssim f_a \ll M_{\rm GUT}$

$$[\mathrm{PQ}, \mathrm{GUT}] = 0 \quad \longrightarrow \quad m_{\psi_{\rm GUT}} = \mathcal{O}(f_a)$$

  - a complete GUT multiplet doesn't help !

Experimental axion searches

- Many different ways to search for axions:
  - Haloscopes (axion DM)
  - Helioscopes (axions from the Sun)
  - Astrophysical bounds
  - New ideas…

Haloscopes

• Look for DM axions with a microwave resonant cavity [Sikivie (1983)]

– exploits <u>Primakoff effect</u>: axion-photon transition in external static E or B field

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma}\, a\, F \cdot \tilde{F} = g_{a\gamma\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$$

– power of axions converting into photons in an EM cavity

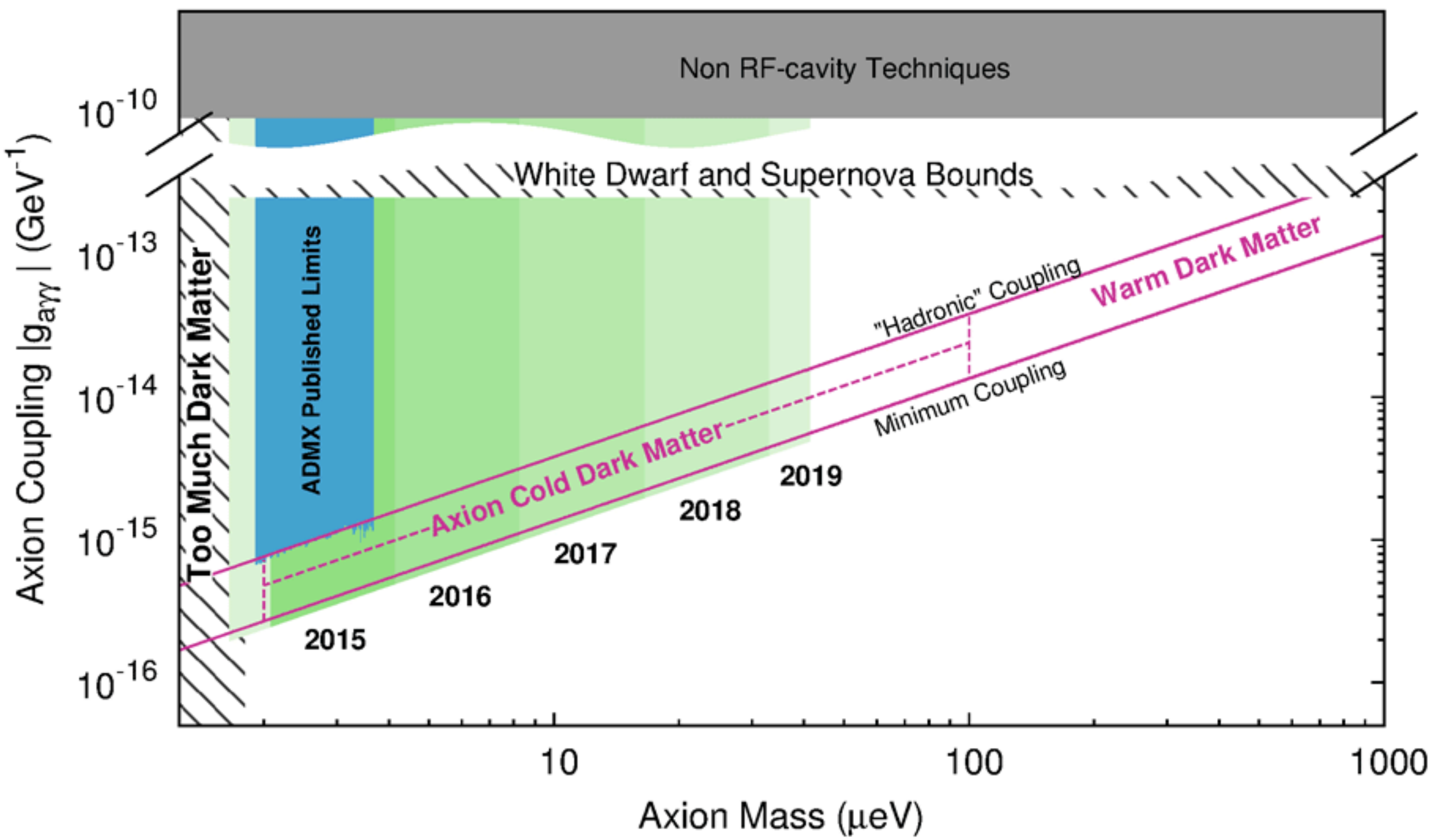
$$P_a = C g_{a\gamma\gamma}^2 V B_0^2 \frac{\rho_a}{m_a} Q_{\rm eff}$$

- resonance condition: need to tune the frequency of the EM cavity on the axion mass

Haloscopes

- Look for DM axions with a microwave resonant cavity

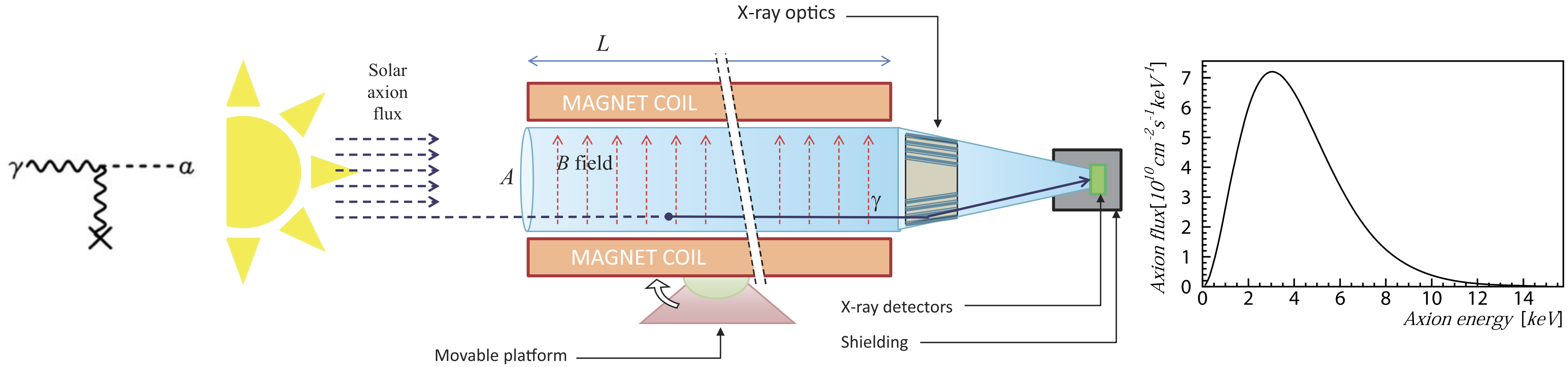
- Axion Dark Matter eXperiment (ADMX) (U. of Washington)



[ADMX Collaboration, 0910.5914]

Helioscopes

- The Sun is a potential axion source



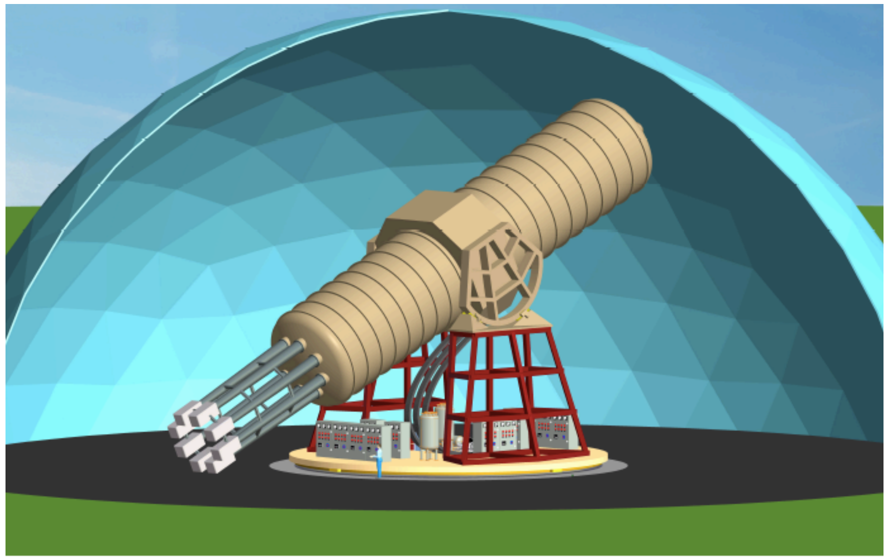
- macroscopic B-field can provide a large coherent transition rate over a big volume

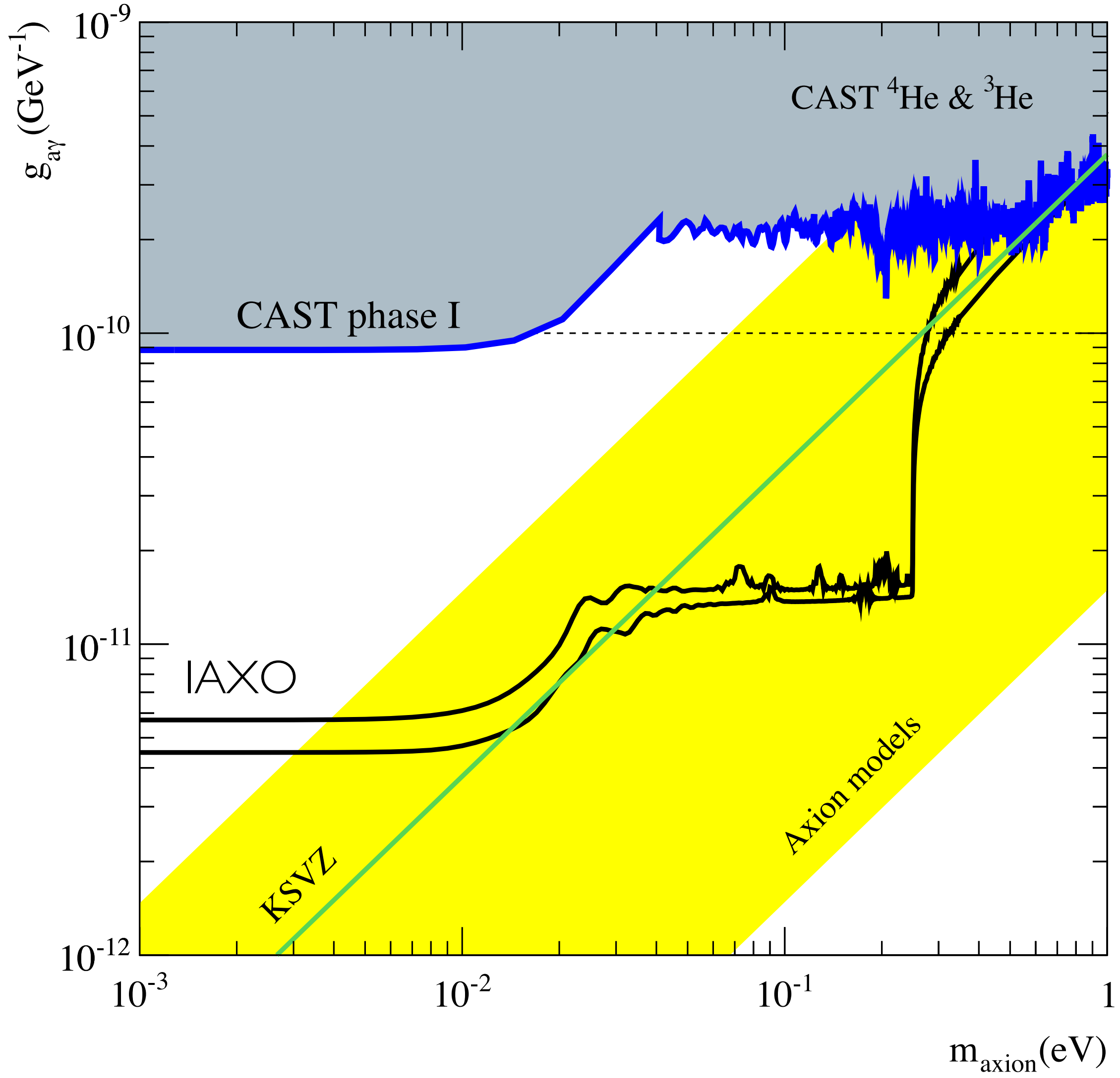
Helioscopes

- The Sun is a potential axion source

  - CERN Axion Solar Telescope (CAST)

  - International AXion Observatory (IAXO)





[IAXO "Letter of intent", CERN-SPSC-2013-022]

Axion couplings to photons

- Axion mass

$$m_a^2 = \frac{m_u m_d}{(m_u+m_d)^2}\frac{m_\pi^2 f_\pi^2}{f_a^2} \qquad\qquad m_a \simeq m_\pi \frac{f_\pi}{f_a} \simeq 6\ \mathrm{meV}\,\frac{10^9\ \mathrm{GeV}}{f_a}$$

$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a}\left[\frac{E}{N} - \frac{2}{3}\,\frac{4m_d+m_u}{m_d+m_u}\right] = \frac{m_a}{\mathrm{eV}}\ \frac{2.0}{10^{10}\ \mathrm{GeV}}\ \left(\frac{E}{N} - 1.92(4)\right)$$

EM anomaly

long distance QCD

EDM of the neutron

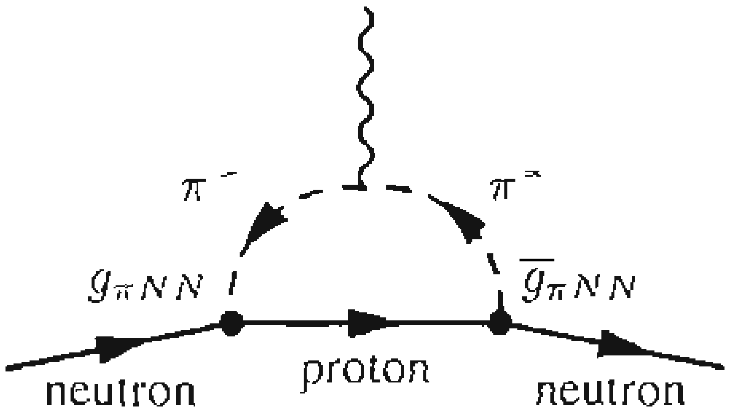
- Estimate from the nucleon-pion effective lagrangian

$$\mathcal{L}_{\pi NN} = \pi^a \bar{\Psi}\left(i\gamma^5 g_{\pi NN} + \bar{g}_{\pi NN}\right)\tau^a \Psi$$

$$g_{\pi NN} = 13.4$$

$$\bar{g}_{\pi NN} = \frac{2m_s m_u m_d}{f_\pi (m_u + m_d)}(M_\Xi - M_N)\bar{\theta} \approx 0.04\bar{\theta}$$

[Crewther et al. (1979)]



$$d_N = \frac{m_N}{4\pi^2} g_{\pi NN}\bar{g}_{\pi NN} \ln\frac{m_N}{m_\pi} = \left(5.2 \times 10^{-16} e \cdot \mathrm{cm}\right)\bar{\theta}$$

$$|d_N| < 2.9 \times 10^{-26} e \cdot \mathrm{cm} \quad \longrightarrow \quad \bar{\theta} < 10^{-10}$$

A threat to the PQ solution

- "Folk's theorem" on the non-existence of global symmetries in quantum gravity

  - global charges can be eaten by black holes, which may subsequently evaporate

[Bekenstein (1972), Zeldovich (1977)]

- Parametrizing explicit breaking by effective operators:

$$\mathcal{O}_{\not{\mathrm{PQ}}} = k \frac{\phi^n}{\Lambda^{n-4}} \quad \xrightarrow{SSB} \quad |k| \frac{f^n}{\Lambda^{n-4}} \cos(na + \arg k),$$

[Kamionkowski, March-Russell (1992), Holman et al. (1992), Barr, Seckel (1992)]

  - for $\Lambda = m_{Pl}$ and $f = 10^9$ GeV :

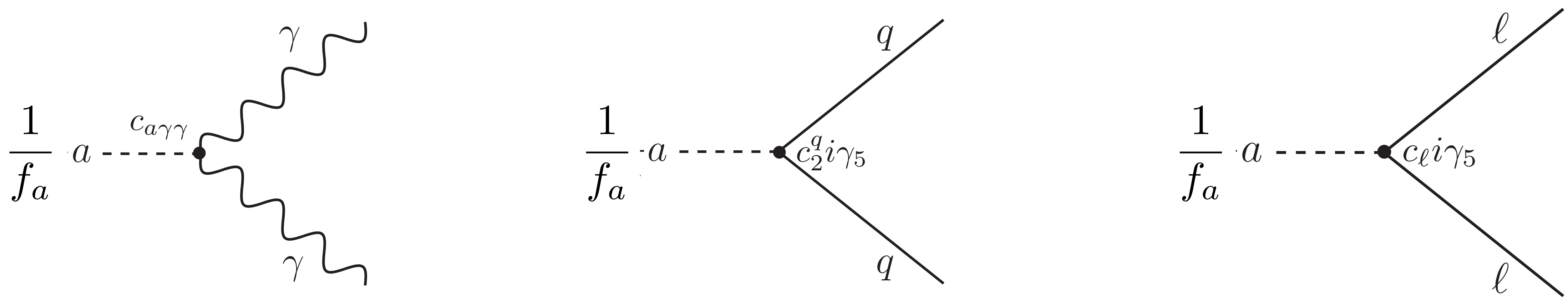
$$\bar{\theta} \lesssim 10^{-10} \quad \longrightarrow \quad n \geq 10$$

Axion couplings at low energy

- Axion mass

$$m_a \simeq m_\pi \frac{f_\pi}{f_a} \simeq 6 \text{ meV} \, \frac{10^9 \text{ GeV}}{f_a}$$

- Axion couplings



photons hadrons leptons

- the lighter the axion, the more weakly interacting